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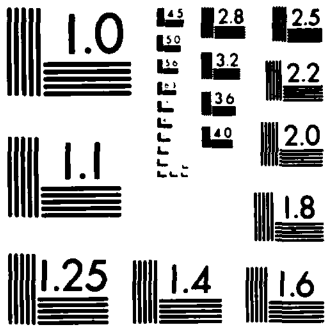

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MESOCYCLONE DETECTION AND CLASSIFICATION ALGORITHM

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June 1983

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A proposed four-dimensional algorithm for automated detection of mesocyclones employs resolution-dependent thresholds of rotational velocity and shear. This algorithm incorporates complementary features of earlier techniques suggested by Hennington and Burgess and by Forsyth, Bjerkaas and Petrocchi. Classification of mesocyclones by calculation of total rotational kinetic energy is proposed as a possible means for early assessment of the destructive energy of the resultant tornado.

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MESOCYCLONE DETECTION AND CLASSIFICATION ALGORITHM

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1.0 INTRODUCTION

Mesocyclones are circulating regions, averaging 5 km in diameter, located within some intense and well-organized thunderstorms. Although infrequent, they are an important aid in providing a storm warning signature detectable by Doppler radar. Nearly all mesocyclones are associated with some form of severe weather, and about half of them spawn tornadoes. The typical mesocyclone starts at mid-levels (about 5 km) in a storm and rather slowly extends upward and downward. Tornadoes and other severe weather manifestations generally do not occur until the mesocyclone base reaches the ground, a process that averages 31 minutes in duration (Burgess et al., 1982). Consequently, detection of a mesocyclone early in its development cycle will yield a far greater lead time for forecasters than is presently available.

Mesocyclones have been successfully detected for many years through visual inspection of the velocity field provided by a single Doppler radar. Accomplishment of this task in real time, however, demands the constant and alert attention of a meteorologist. Economical and reliable employment of human resources in an operational scenario requires the aid of an automated mesocyclone detection scheme. Automation is especially needed during tornado outbreaks, when two or more mesocyclones may occur simultaneously within range of a radar.

It is proposed that this automatic processing be performed by a four-dimensional detection algorithm that identifies mesocyclonic shear with a resolution-dependent shear threshold applied over a minimum velocity difference. These criteria are intended to enable the algorithm to detect small mesocyclones, and large ones at great ranges (where impaired azimuthal resolution may reduce measured shear) without triggering false alarms due to natural small-scale variability in velocity. This proposed algorithm will vertically correlate mesocyclonic shear features and tabulate their temporal persistence.

The development of this four-dimensional mesocyclone detection algorithm is a natural extension of less comprehensive algorithms proposed by Hennington and Burgess (1981) and by Forsyth et al. (1981). These earlier algorithms have some complementary features. The former detects mesocyclonic shear based on a combination of shear and momentum thresholds, and computes the horizontal extent of the circulation in radial as well as azimuthal direction. The latter scheme is based only on shear between velocity peaks and correlates this shear vertically and temporally.

Momentum thresholding was not incorporated in our mesocyclone detection algorithm because of its tendency for rejection of small but intense vortices, such as tornadic vortex signatures, and for acceptance of certain large-scale patterns with less than the requisite shear. We suggest, however, that mesocyclones be classified by the trends of their rotational kinetic energy, and angular momentum. This may be a means for early assessment of the destructive energy of the resultant tornado. For vortices of equal size, rotational kinetic energy is proportional to the <u>square</u> of maximum rotational velocity, so this parameter may be especially sensitive as an indicator of the probability of a tornadic circulation penetrating to the ground and inflicting severe damage.

2.0 PROPOSED ALGORITHM

The algorithm is capable of detecting cyclonic and anticyclonic circulations over a wide range of scales. It computes the horizonal and vertical extent, average shear, momentum, rotational kinetic energy and temporal persistence of these circulations.

Criteria for the detection of mesocyclones have been set forth by Donaldson (1970), and later by Burgess (1976). Three basic requirements are: 1) significant azimuthal shear must exist between closed velocity contours of opposite sign (provided storm motion has been removed). 2) Shear pattern and closed isodops must extend vertically for a height interval comparable to the horizontal diameter. 3) The shear pattern must persist for a time interval greater than one half of the revolution period of the feature.

Burgess et al. (1982) defined the evolutionary stages of mesocyclones: 1) The organization stage is characterized by growth of the circulation area upward and downward, from mid-levels. Convergence as well as rotation may be revealed in the low-level signatures. The organizing stage ends when the mesocyclone's base extends to the lowest elevation scan. 2) The mature stage is characterized by a period of maximum velocities. During this stage tornado potential is greatest. The mesocyclone may show some convergence at lower levels, pure core rotation at middle levels, and some divergence at the top. Generally the top of the circulation is slightly lower than the peak during the organization stage. 3) The dissipating stage begins when the mesocyclone summit drops rapidly, and the maximum velocities decrease. At the end of this stage the circulation exists in a shallow layer and is very weak.

2.1 Scale Considerations

Although a great majority of mesocyclones and tornadoes are cyclonic, a few anticyclonic tornadoes have been observed. Therefore, we have ensured that the algorithm can detect anticyclonic circulations. Since mesocyclones have long been recognized as the vorticity-producing source for tornadoes we have included the detection of tornado vortex signatures (TVS's) in our algorithm. The algorithm is capable of detecting many scales of meso-circulations. For all practical purposes we shall confine our analysis to only those scales between a small TVS and a large mesocyclone, that is, from several hundred meters to 20 km in horizontal extent.

2.2 Algorithm Processing

This algorithm has evolved from a two-dimensional mesocyclonic shear algorithm proposed by Hennington and Burgess (1981) (further developed by Zrnic et al. (1982)) and a three dimensional mesocyclone-TVS algorithm developed by Forsyth et al. (1981). We have modified and merged these algorithms so that they process data in close to real time and automatically archive mesocyclone attributes for later analysis.

The algorithm processing can be broken into five steps. These are:

1) The algorithm searches for gradients in the Doppler velocity field. This is accomplished by identifying either increasing or decreasing velocities in the azimuthal direction.

2) When a run of constantly increasing or decreasing velocities ends, the shear along the run is tested. If the shear exceeds a resolution dependent threshold a pattern vector is formed by joining peaks in the velocity field at constant range. The following six attributes of pattern vector are saved: beginning and ending azimuths $\phi_b \phi_e$, beginning and ending velocities $V_b V_e$, range to the pattern vector, and time of the beginning azimuth.

3) After each azimuth scan is completed the pattern vectors are grouped together into a two-dimensional feature. The tests for association of two pattern vectors are close radial proximity (less than 1 km), and azimuthal overlap. The two-dimensional features that have a radial extent of 0.6 km (4 range gates) or more are saved for vertical correlation with higher elevation scans. The attributes saved for each two-dimensional feature are: the number of pattern vectors in the feature, minimum and maximum azimuth, beginning and ending range, and the minimum and maximum peak velocities and their orientation with respect to the radar beam.

4) The vertical correlation consists of comparison of the locations of features observed at successive elevations. If the distance between the centroids of the two-dimensional features is less than the sum of their diameters they are assumed to be correlated and their attributes are averaged for comparison with features from the next highest azimuth scan. This process continues until the end of a volume scan at which time the attributes of the three-dimensional features are analyzed.

5) As recommended by Donaldson (1970) and Burgess (1976) the shear pattern for a mesocyclone should persist for one half the period of the vortex rotation. The algorithm computes the persistence of a feature and sets a flag when this criterion has been met.

The first test on a three-dimensional feature is a check for cyclonic and anticyclonic circulation. Next the azimthal and radial diameters are checked, and if they are not within 50 percent of one another the feature is labeled a shear area. Otherwise, the diameters are compared to the vertical depth of the feature. If they are within 50 percent of one another the feature is called a mesocyclone. When the shear for a mesocyclone exceeds the resolution-dependent threshold for TVS it is labeled as a tornado. Two-dimensional features that are only observed at one elevation are called single-height features.

The results from this analysis can immediately be written to a screen for operator interpretation, and to a hard copy device. The mesocyclone's average shear, momentum, rotational energy, and identification number are stored for future analysis.

2.3 Resolution-Dependent Shear Threshold

In order to compensate for the cross-beam degradation of resolution with range we have applied resolution-dependent thresholds for shear and peak velocity difference as criteria for retaining pattern vectors.

Hennington and Burgess (1981) and Zrnic et al. (1982) used a combination of momentum and shear thresholds to determine if a pattern vector is saved for further processing. In order to detect smaller circulations (e.g., TVS) we have eliminated the momentum thresholding because it implies a minimum length for a pattern vector. The momentum of a pattern vector is estimated from the product of the measured velocity difference (V_e-V_b) and the azimuthal distance $R(\phi_v-\phi_e)$; shear is the quotient of these two quantities.

The velocity pattern around a non-divergent mesocyclone is generally modeled by a Rankine combined vortex (RCV). This means that the core of the mesocyclone, defined as the region between velocity peaks of opposite sign, is assumed to rotate as a solid body. As the mesocyclone is moved out in range the peak velocities decrease significantly as more and more of the mesocyclone is encompassed by the radar pulse volume. At the same time the diameter of the feature appears to increase.

We have derived our shear dependence by considering the effect of increasing range of the resolution of a RCV. Brown and Lemon (1976) present some enlightening results of a RCV model developed by Zrnic and Doviak (1975). The paper addresses the problem of identifying a TVS described by a RCV as it is moved out in range.

In this analysis we have assumed data are collected at increments equal to the antenna beamwidth. The basic indicator of the resolution dependence of a feature is the ratio of the radar beamwidth (BW) to core radius (CR). If this ratio is much less than 1 the radar can resolve the meso-circulation fairly well. As the ratio increases there is a degradation in the observed feature. At beamwidth to core ratios greater than 2 the true attributes of the feature are difficult if not impossible to resolve.

A minimum azimuthal shear of 5×10^{-3} s^{-1} for mesocyclone detection was first proposed by Donaldson (1970) and later corroborated by Burgess (1976) from a study of several years of mesocyclone data. If we assume that an azimuthal shear of $5 \cdot 10^{-3}$/s is a practical cut-off between mesocyclonic and non-mesocyclonic storms, and that the minimum allowable velocity difference is 15 m/s, we can see that the smallest, lowest shear mesocyclone we will permit is 3 km in diameter. With a beamwidth (α) of 0.8 degrees we can easily resolve this feature out to a range of 110 km (BW = 1.5 km), after which the beamwidth to core radius would be greater than 1. At 220 km our beamwidth is approximately 3 km or twice the core radius of the RCV. Brown and Lemon's data show that a beamwidth twice the core radius would smooth the peak velocities to approximately 62 percent of their original magnitude, and the core radius would appear to be slightly larger than its true size. Consequently the shear reported for the feature would be somewhat less than 62 percent of the "true" shear. If the ratio of the beamwidth to the core radius of a tornadic feature is large, the apparent core radius can be much larger than the actual size. For example, when the beamwidth is 3 times the core radius the peak velocities detected by the radar may be 1.5 core radii from the center of the rotation.

An illustration of the momentum and shear thresholds used by Zrnic et al. (1982) can be seen in Fig. 1.

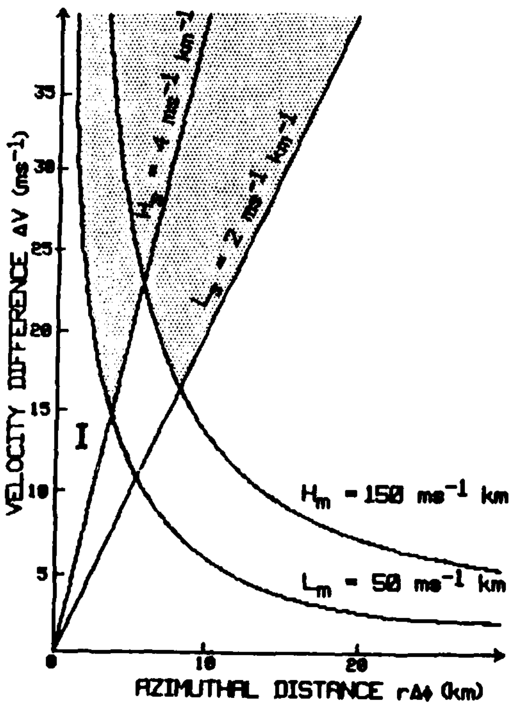

Fig. 1. Mesocyclone detection thresholds suggested by Hennington and Burgess (1981) portrayed in terms of velocity difference and azimuthal distance across a shear pattern. H_s and L_s are lines of constant shear, and H_m and L_m are lines of constant angular momentum. A shear pattern falling into the shaded area is accepted as a mesocyclone. In region I, which includes many high-velocity tornado vortex signatures, all shear patterns would be rejected.

The shaded region of this figure represents the mesocyclone detection region. These thresholds do not permit the detection of TVS's, as the low momentum threshold precludes small but intense vorticies. Since no objective criteria for the detection of TVS's have been established we shall use the guidelines adopted during the Joint Doppler Operational Project (Burgess, et al. 1979). These are the presence of shear greater $5 \cdot 10^{-2}$ and a rotational velocity greater than 30 m/s. This feature could have a diameter of less than 1.5 km and would be in region I of Fig. 1, and precluded from further processing with the original momentum thresholding.

Fig. 2 is a representation of our resolution-dependent shear threshold.

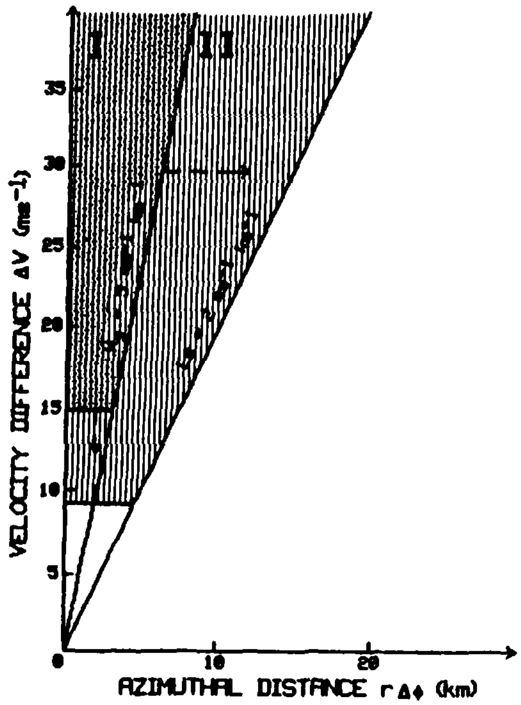

Fig. 2. Mesocyclone detection threshold (including TVS's) suggested in the present paper, portrayed in terms of velocity difference and azimuthal distance across a shear pattern. A shear pattern observed with perfect azimuthal resolution (Beamwidth/Core Radius = 0) would be accepted as a mesocyclone if it fell into region I. With decreasing resolution both the shear and velocity difference thresholds would be relaxed in the direction of the dashed arrows. For a Beamwidth/Core Radius = 2, the mesocyclone acceptability space is expanded to include region I and all of region II.

The hatched region (II) of this figure represents the sliding mesocyclone detection region, and the shaded region (I) represents the perfect resolution thresholds. Using the resolution-dependent shear threshold one can see that the TVS discussed above would be included in processing. The shear threshold decreases and the minimum velocity difference decreases as the BW/CR ratio increases. The constant shear and velocity difference lines in Figure 2 represent the extreme of the thresholds used in the algorithm. Assuming perfect resolution of a feature we apply a $5 \cdot 10^{-3}$ shear threshold and a velocity difference threshold of 15 m/s. As the BW/CR ratio increases we gradually decrease the shear and velocity difference thresholds to $2 \cdot 10^{-3}$ and 9.3 m/s at BW/CR = 2.

3.0 MESOCYCLONE CLASSIFICATION

Burgess (1976) provided the earliest detailed classification of mesocyclones. In the first four years of single-Doppler data acquired by NSSL, the average difference in rotational velocity between tornadic and non-tornadic mesocyclones was less than 3 m s^{-1}. However, the few mesocyclones which produced maxi-tornadoes had rotational velocities averaging more than 10 m s^{-1} greater than the non-tornadic ones. These early statistics showed very little, if any, predictive value for tornado occurrence among mesocyclones. They do, however, suggest that the heavily-damaging maxi-tornadoes, which injure and kill a disproportionately large number of people, may be preceded by mesocyclones having unusually large rotational velocities.

Carrying this thought a step further, it seems to us that classification of mesocyclones according to their rotational kinetic energy could be even more useful than rotational velocity or angular momentum. Rotational kinetic energy is proportional to the square of velocity, so the mesocyclones with higher velocities would be emphasized more than those of larger size. Integration of rotational kinetic energy with height would provide an energy index for each volume scan, and could be an aid in tracing the evolution of a mesocyclone. The trend of total rotational kinetic energy in a mesocyclone may enhance the ability of a forecaster to predict the touchdown of a maxi-tornado.

4.0 PRELIMINARY RESULTS

As a test of the algorithm we have processed several volume scans of data collected during JDOP (Burgess et al 1979). Our test data are from April 30, 1978 starting at 1810 CST, just prior to the Piedmont tornado touchdown. In the first volume scan the algorithm identifies a well developed mesocyclone. Output from the second volume scan reveals that the mesocyclone is moving to the east and that there is a two-dimensional TVS shear at elevation angles of 5.0 and 6.9 degrees, the peak velocities at these levels being 33 and -36 m/s. When the antenna drops down for the next volume [illegible] CST) we have a two-dimensional TVS shear with peak velocities of 35 and -36 m/s at 100 m above ground level. On the completion of the third volume scan the algorithm identifies a three-dimensional TVS.

The Piedmont tornado touched down at 1820 CST, at which time the radar was scanning at high elevation angles. The development of this tornado was rapid at low levels, the tornado was on the ground by the time the antenna dropped to [illegible] degrees. This feature is identified by the algorithm in two more volume scans and appears to weaken slightly although maintaining very strong shear.

5.0 CONCLUSIONS

A resolution-dependent pattern recognition algorithm for detecting mesocyclones and tornado vortex signatures has been developed.

The algorithm identifies three-dimensional cyclonic and anticyclonic [illegible] computes their average shear, angular momentum, and rotational kinetic energy. The time continuity of the detected features is confirmed by a persistence criterion, and the peak velocities at every elevation angle are recorded.

Initial tests of the algorithm appear to be promising. More studies must be done in this area to improve our understanding of mesocyclones and the mechanisms involved as they spawn tornadoes. The interactions between a mesocyclone's momentum, shear, and kinetic energy as it follows its life cycle should yield some valuable statistics regarding the potential destructive power of the circulation.

Further refinement of the algorithm is likely to take place as more data is processed. In particular the minimum feature size, the velocity difference and shear thresholds, and the beamwidth to core radius ratio cut-offs can only be evaluated after extensive testing. Probability of detection and false alarm statistics need to be compiled over a wide range of cases in order to give us better understanding of the algorithm's performance.

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